Auditory Masking Patterns in Bottlenose Dolphins from Anthropogenic and Natural Noise Sources

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LONG-TERM GOALS

The long-term goals of this project are to better understand and predict auditory masking in odontocetes with realistic, environmental noise types. Current predictions based on Gaussian noise masking will be improved upon.

OBJECTIVES

The objectives of this effort are to understand and predict how environmental noise (both anthropogenic and natural) affects detection, discrimination, and recognition abilities of odontocete cetaceans. The specific objectives for FY12 were to:

- Develop and test hypotheses to describe auditory masking patterns from FY10 and FY11
- Develop predictive quantitative models to describe masking with environmental noise
- Estimate auditory recognition thresholds with different noise types

APPROACH

The primary goal of the current project is to better understand auditory masking by determining masking patterns for a broad variety of environmental noise types, and define the mechanisms that govern auditory signal processing in environmental noise. Behavioral threshold methods developed at SSC San Diego (Finneran, Carder, Schlundt, & Ridgway, 2005) allow thresholds to be obtained rapidly (i.e., less than four minutes). Behavioral thresholds are measured using a psychophysical technique, such as modified up/down adaptive staircase. The procedure for estimating masked thresholds is identical to a standard behavioral hearing test except masking noise is played continuously during the threshold estimation procedure.

Study 1. Masked detection thresholds as a function of signal-band phase delay
Previous experiment from FY10 demonstrated that noise with across-channel envelope coherence (ACEC) leads to comodulation masking release (CMR). Auditory detection thresholds in comodulated noise were manipulated by varying the degree of ACEC by bandpass filtering the noise into a signal

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band (9.5 kHz – 10.5 kHz) and two flanking bands (low flank: 6 kHz – 9 kHz, high flank 11 kHz – 14 kHz; see FIG 1). When the signal band is delayed in time, relative to the flanking bands, masked detection thresholds for a 10 kHz signal increased, presumably due to a lack of ACEC. To determine if thresholds in different noise types were governed by this mechanism, we repeated this experiment with four noise types: Gaussian (G), comodulated (CM), snapping shrimp (SS) and ice squeaks (IS).

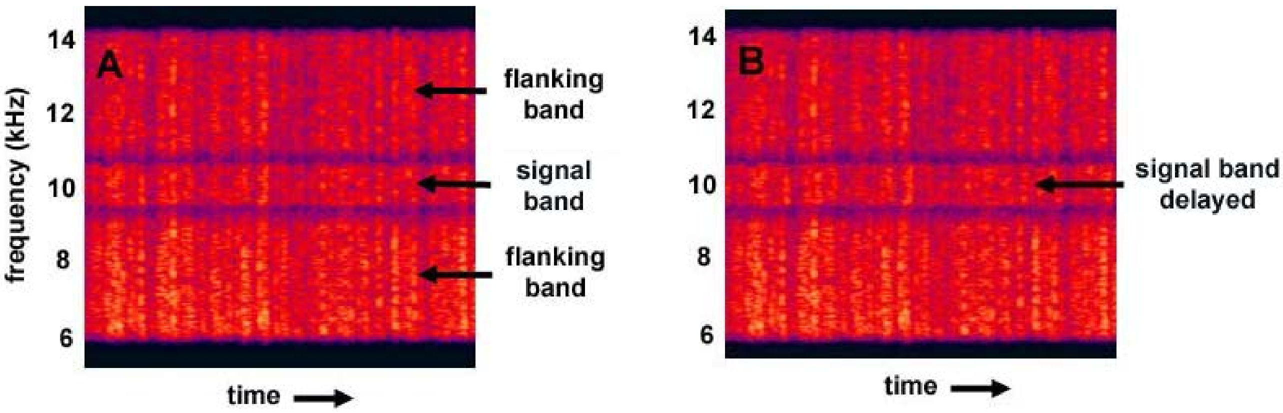

FIG. 1. Noise stimuli used in the phase delay study. (A) The signal band and flanking bands are in phase. (B) The masking band is delayed and out of phase.

Study 2. Describing auditory masked detection with the magnitude-squared coherence.
Several lines of evidence (Branstetter & Finneran, 2008) suggest the amount of ACEC is a major factor in determining masked thresholds. A metric was developed to quantify the amount of ACEC in noise samples used in previous masking experiments. First, noise was bandpass filtered into a signal band (9.5 kHz – 10.5 kHz) and two flanking bands (low frequency: 8-9 kHz, high frequency:11-12 kHz). The bandwidths of these filters approximate critical bandwiths at these frequenies (Branstetter & Finneran, 2008). The Hilbert envelope (*env(t)*) was extracted from the output of each channel:

$$env(t) = \sqrt{f(t)^2 + h(t)^2} \tag{2}$$

where *h(t)* is the Hilbert transform of the waveform *f(t)*. The magnitude squared cohrence (MSC) was estimated between the $env_s(t)$ and $env_{lf}(t)$, and between $env_s(t)$ and $env_{hf}(t)$, where $env_s(t)$, $env_{lf}(t)$, and $env_{hf}(t)$ are the Hilbert envelopes from the signal band, the low frequency band, and the high frequency band respectivly. The magnitude squared coherence can be calculated by:

$$C_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)} \tag{3}$$

Where x and y are the two Hilbert envelopes being compared, $P_{xx}(f)$ and $P_{yy}(f)$ are the cross power spectral densities of x and y, and $0 \le C_{xy}(f) \le 1$. The results are MSC estimates as a function of frequency. To simplify the metric, the single largest MSC is selected between the two vectors, regardless of frequency, resulting in a single value that represents the maximum level of ACEC. We tested if there was a relationship between masked auditory thresholds and MSC for a variety of noise types.

Study 3. Masked detection thresholds as a function of ACEC and pressure spectral density
In previous experiments from FY10 and FY11, different noise types resulted in threshold differences (as large as 22 dB) even though the pressure spectral density of each noise type was 95 dB (re 1 μPa^2 / Hz). The amount of ACEC appears to account for much of this variance. However, thresholds have not been estimated with different spectral density levels. We hypothesized that a general linear model including both ACEC and spectral density levels could accurately predict masked detection thresholds in dolphins. Comodulated noise, with varying levels of ACEC was synthesized by multiplying Gaussian noise by low-pass noise, where the low-pass cutoff varied between 100 Hz and 1000 Hz. A dolphin was required to detect a 10 kHz tone masked by the synthesized noise (bandwidth 6 kHz to 14 kHz), where the noise was presented at 85, 90, 95, and 100 dB (re 1 μPa^2 / Hz)

Study 4. Comparison between detection, and recognition thresholds in complex noise
Noisy environments have the potential to not only compromise an animal's ability to detect a signal, but can also interfere with an animal's ability to recognize important features of signals. Specific communication signals in marine mammals likely serve specific functions including mating displays, fighting assessment, recognition of group members and individuals, maintaining group cohesions, and maintaining individual social relationships (Tyack & Clark, 2000).

For estimating recognition thresholds, a dolphin learned to associate a differential response with each of the three whistle-like sounds in FIG 2. For example, when the sound in FIG. 2A was presented, the dolphin was trained to swim and touch a nylon rope (FIG. 3). If the sound in FIG. 2B was presented, the dolphin swam and touched a water filled aluminum bottle. All three signals had identical bandwidths between 8 kHz and 12 kHz and only differed by their frequency modulation pattern. Masking noise was played continuously, with a flat frequency spectrum (95 db re 1μPa^2 / Hz) between 6 kHz and 14 kHz. The noise types chosen for this experiment were G, CM, SS and IS. Previous experiments from FY10 demonstrated that these noise types result in a wide range of masked detection thresholds. The level of the signal was randomly adjusted on each trial (method of constants) to estimate psychometric functions (proportion of correct object choice as a function of signal level).

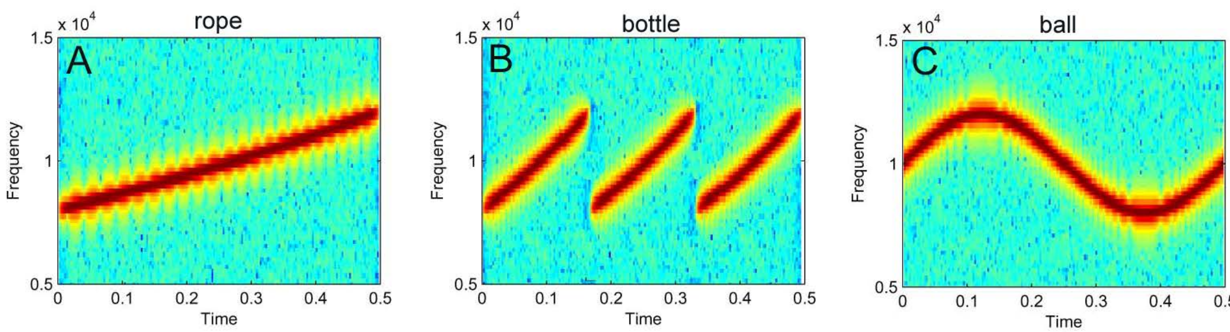

FIG. 2. Frequency modulated stimuli used in the masked discrimination experiment.

Key personnel
Key personnel for FY2012 have been Brian Branstetter Ph.D. (PI) who participated in all aspect of this study. Kimberly Bakhtiari, Hitomi Aihara, Amy Black and Keri Wickersham helped with animal training and data collection. James Finneran Ph.D developed custom Labview software.

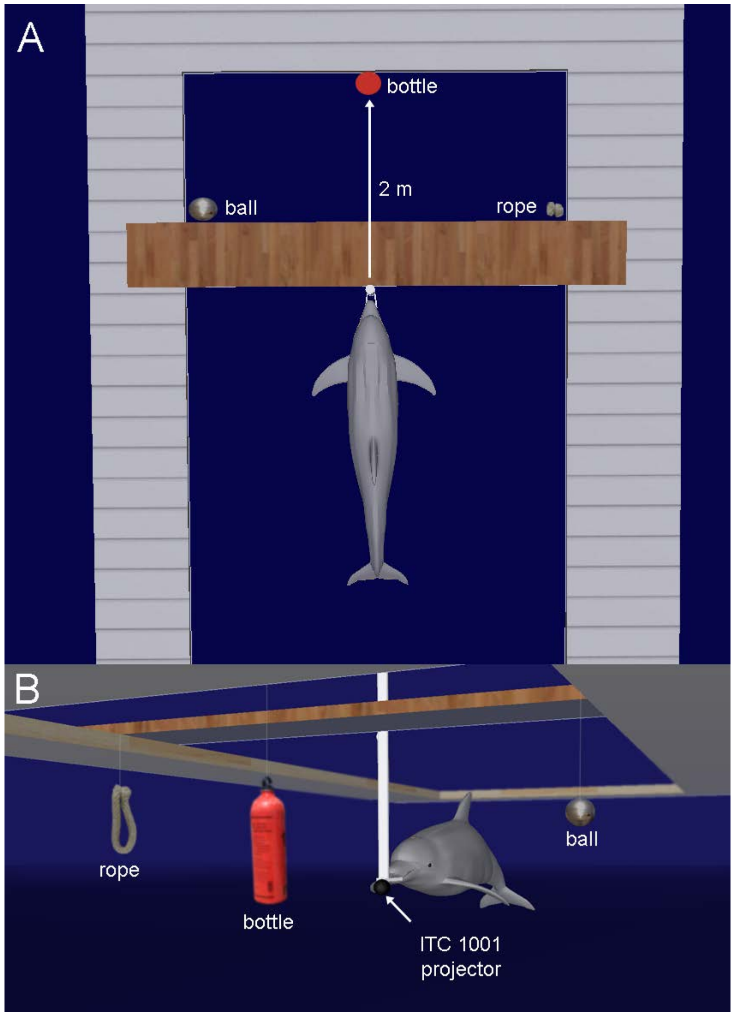

FIG. 3. Experimental apparatus. The dolphin was trained to station on an underwater neoprene bite plate with an ITC 1001 projector mounted on the apparatus. Three objects were postioned at the same depth as the dolphin at equal radial distances of 2m from the bite plate. The dolphin was required to swim and touch one of the objects in response to learned associations with whistle-like sounds (FIG, 2). For example, if the sound for "ball" was played (from FIG. 2), the dolphin was required to swim and touch the ball in order to receive fish reinforcement.

WORK COMPLETED

Masked detection thresholds as function of signal-band phase delay.

Detection thresholds were measured for four noise types (G, CM, SS, and IS). Thresholds were averaged for each noise type and each signal band delay. T-tests were conducted between the delays of 0 ms and 1000 ms conditions, within each noise type, to determine if across-channel envelope coherence was a mechanism governing thresholds. The dolphin in this experiment was APR.

Describing auditory masked detection with the magnitude-squared coherence.

Threshold data were pooled from four experiments that included seven noise types with three dolphin subjects (SAY, BOB, and APR). A total of 20 data points (each point represents the average of four thresholds) were used in the analysis. The MSC was measured for each noise type and a linear regression performed where MSC was a predictor of detection thresholds. The ability of MSC to predict thresholds was compared to critical ratio predictions.

Masked detection thresholds as a function of ACEC and pressure spectral density

Two experiments were completed. The first experiment estimated thresholds in seven noise types at two different dB levels (total of 14 conditions, four thresholds / condition). The noise was comodulated (i.e., Gaussian noise multiplied by low-pass noise), but the low-pass filter (lp) varied (lp=100, 250, 500, 1000, 2000, 5000 Hz). Gaussian noise was used as a control. This experiment focused on determining the effect of ACEC on thresholds. A second experiment was conducted with three noise types (lp=100 Hz, lp=1000Hz, Gaussian) at 4 dB levels (85, 90, 95, 100 dB) for a total of 12 conditions (four thresholds / condition). This experiment examined the relationship between thresholds, noise spectral density level, and ACEC. The dolphin in this study was APR.

Masked Recognition Thresholds

Psychometric functions (proportion correct vs. signal level, proportion no response vs. signal level) were estimated for three signal types (FIG. 2) masked by G, CM, SS, and IS noise. The data were collected in an ABBA counterbalanced format to reduce learning effects. Psychometric functions were estimated using logistic regression with binomial errors. The dolphin in this experiment was SAY.

RESULTS

Masked detection thresholds as a function of signal-band phase delay

The effect of delaying the signal band relative to the flanking bands resulted in a significant threshold difference for both comodulated and snapping shrimp noise (FIG. 4). There was no significant effect for Gaussian or ice squeak noise. These data support the hypothesis that a release from masking will occure in amplitude modulated noise (e.g., comodulated and snapping shrimp) and the release will be most salient if the ampliude modulation is coherent across frequency regions. Models that attempt to predict auditory masking should incorporate a statistic that reflects levels of ACEC (see results next section).

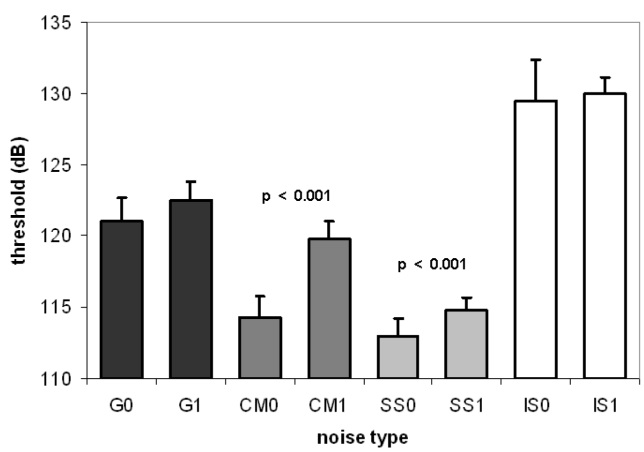

FIG 4. Masked detection thresholds as a function of noise type and signal band delay. Each noise type (G = Gaussian, CM = comodulated, SS = snapping shrimp, and IS = ice squeaks) is followed by a number representing the delay of the signal band relative the flanking bands (0s or 1s). There was a significant difference (p < 0.001) between delays for CM and SS noise.

Predicting auditory masked detection with the magnitude-squared coherence.
The dashed line in FIG. 5 represents threshold predictions based on the dolphin's critical ratio estimated from a Gaussian noise masker. The solid line represents a linear model (see equation in FIG. 5) which provided much better fits to all noise types except ice squeaks. These data strongly suggest that incorporating a metric related to ACEC (i.e., MSC) dramatically improves thresholds predictions. Although model fits are good, the model fails to accommodate changes in noise spectral density levels (all noise types had a spectrum level of 95 dB re 1 μPa^2 / Hz). The next section addresses this shortcoming.

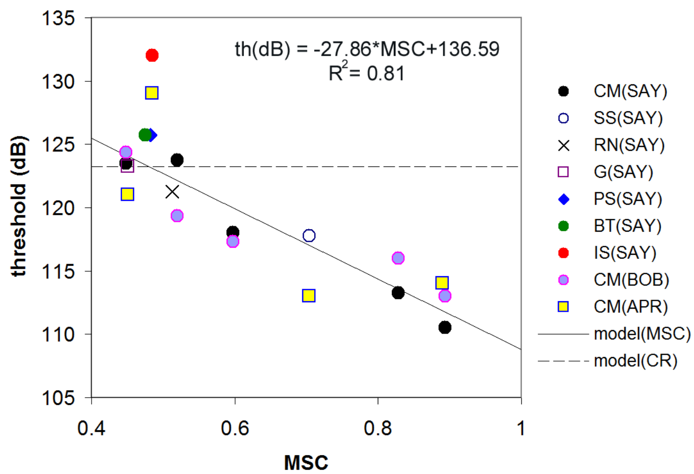

FIG. 5. Thresholds as a function of MSC. CM=comodulated, SS = snapping shrimp, RN = rain, G = Gaussian, PS = pile saw, BT = boat, IS = ice squeaks. Three dolphins participated: SAY, BOB, and APR. Model (MSC) is based on the equation (upper left). Model(CR) is based on CR predictions.

Masked detection thresholds as a function of ACEC and pressure spectral density
FIG. 6(A) represents thresholds as a function of different types of comodulated noise (i.e., Gaussian noise multiplied by low-pass noise). Comodulated noise created with a low-pass filter with a lower high frequency cutoff resulted in lower thresholds. FIG. 6(B) plots the same threshold data but noise type is replaced with its respective MSC. Dashed lines represent linear model fits of the form:

$$L_s = -37.51*MSC + 1.1947*dB+29.51 \tag{4}$$

Where L_s is the level of the signal at threshold, MSC is the magnitude squared coherence and dB is the spectral density of the noise (re 1 μPa^2 / Hz). This model improves upon the linear fit from the previous section by accounting for changes in spectral density levels. Threshold data for four spectral density levels of (85, 90, 95, and 100 dB) and several noise types are plotted in FIG. 7 along with a surface plot. The surface plot represents predictions from the quadratic model:

$$L_s = 107.17*MSC^2 + 0.01*dB^2 - 0.04*MSC*dB - 179.12*MSC - 1.53*dB + 201.66 \tag{5}$$

Model fits are displayed in Table 1. The linear(dB) model is equation 4 without the MSC term. This model is equivalent to CR models where only the spectrum level of noise is used to make predictions. The linear(dB, MSC) model is equation 4 and the quadratic(dB, MSC) model is equation 5. The two model that incorporate both spectral density levels (dB) and ACEC levels (MSC) have much more explanatory power indicated by adjusted R^2 and mean square residual values.

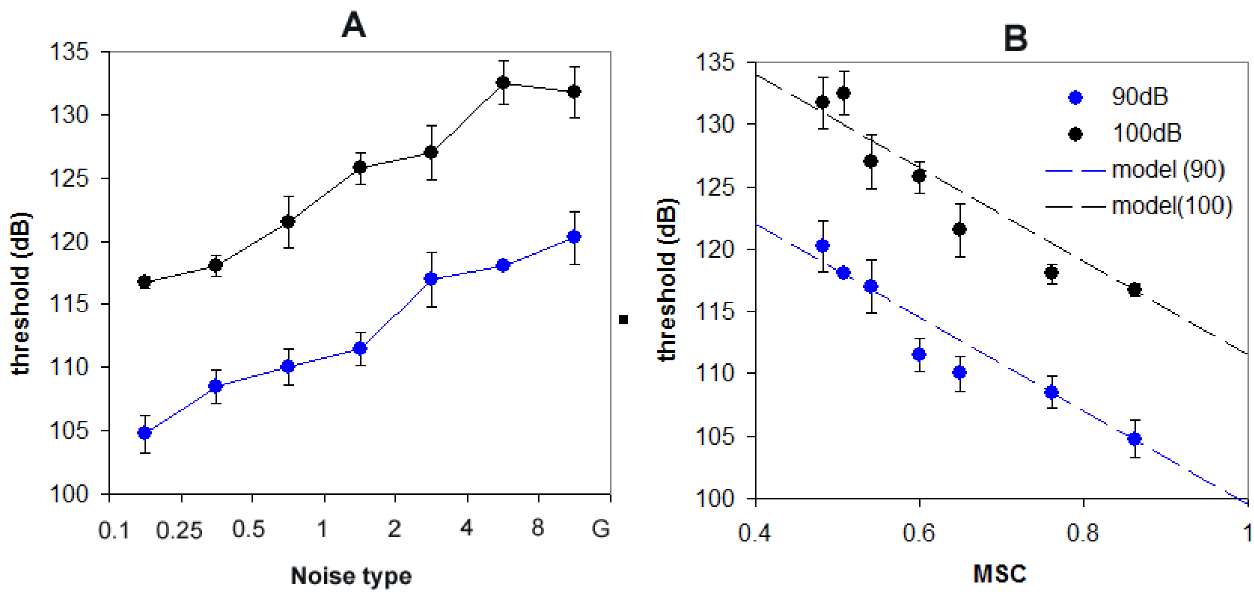

FIG. 6. Masked detection thresholds as a function of noise type and MSC. (A) x-axis represents different comodulated noise (Gaussian noise multiplied by low-pass noise) where the values of the x-axis represent the low-pass filter cutoff in kHz and G represents Gaussian noise. Thresholds increase as the low-pass filter increases. Blue and black data points represent noise with spectral densities of 90 dB and 100 dB respectively. Error bars represent standard deviations. (B) The MSC of each noise type in (A) was calculated and plotted with its respective threshold. Thresholds decrease with increased MSC. Dashed lines are linear fits (equation 4) to the data.

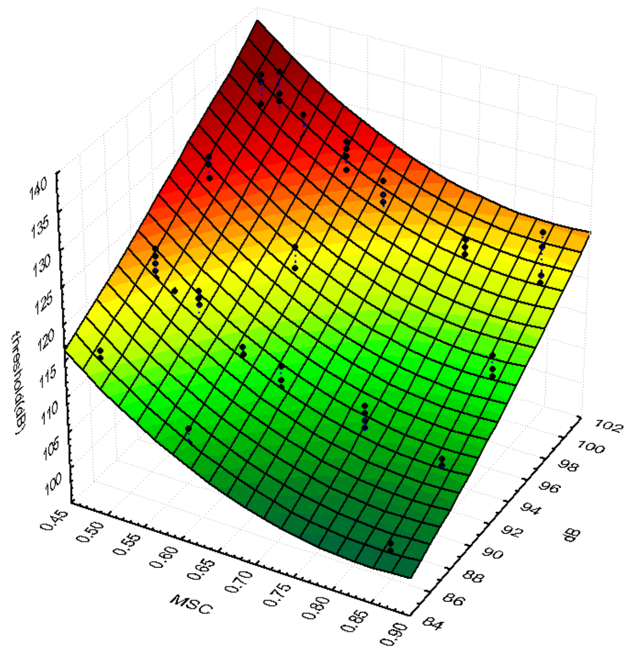

FIG 7. Surface plots of a quadratic model where thresholds are a function of MSC and spectral density level (dB). Black points represent threshold data.

Table 1. Comparison of model fits and residuals. Model type, adjusted R^2 and mean square (MS) residuals are displyed for each model.

Model	**adj R^2**	**MS residuals**
linear (dB)	0.55	35.40
linear (dB, MSC)	0.93	5.89
quadratic (dB, MSC)	0.96	3.40

Masked Recognition Thresholds

Psychometric functions for proportion of correct responses (FIG. 8) and proportion of no responses (FIG. 9) as a function of signal level were estimated. "Proportion correct" functions are a measure of the dolphin's ability to recognize a sound and correctly select the object that the sound is associated with. "No response" functions measure how often the dolphin did not respond to the sound (i.e., the dolphin never left the bite plate to touch an object). Thresholds estimated from no response functions are similar to masked detection thresholds in FIG. 4. Assuming the no response thresholds represent detection thresholds, recognition thresholds are on average 3.75 dB greater than detection thresholds (FIG 10). This trend remains the same regardless of noise type. Therefore, recognition thresholds for whistle like sounds can be predicted by simply adding about 4 dB to detection thresholds.

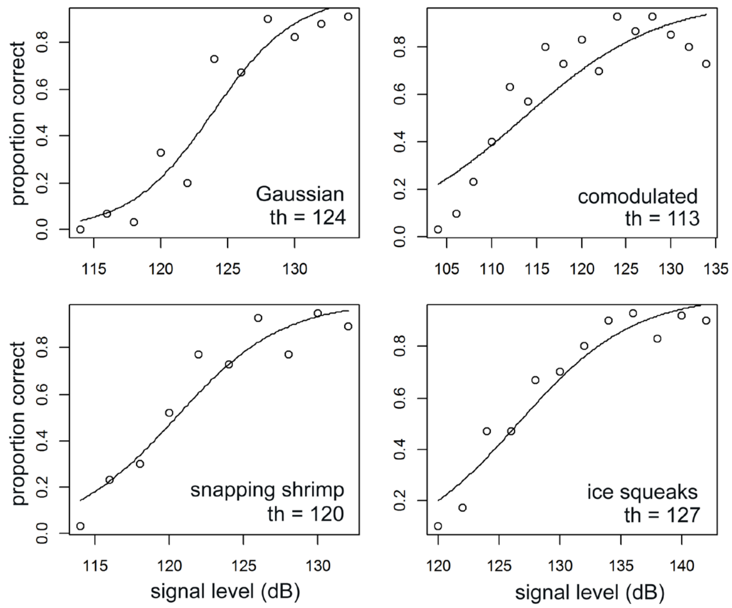

FIG. 8. Recognition thresholds for four different noise types. The data point represent the average proportion correct for all three sound-objects associations. Thresholds (th) were estimated from 0.5 proportion correc levels.

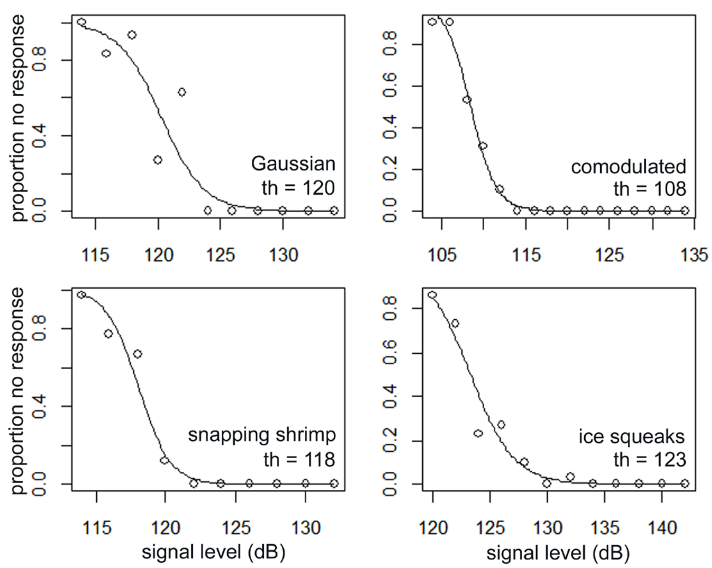

FIG. 9. No response thresholds for four different noise types. Data represent proportion of no-responses as a function of signal level. Thresholds (th) were estimated from 0.5 proportion no response levels.

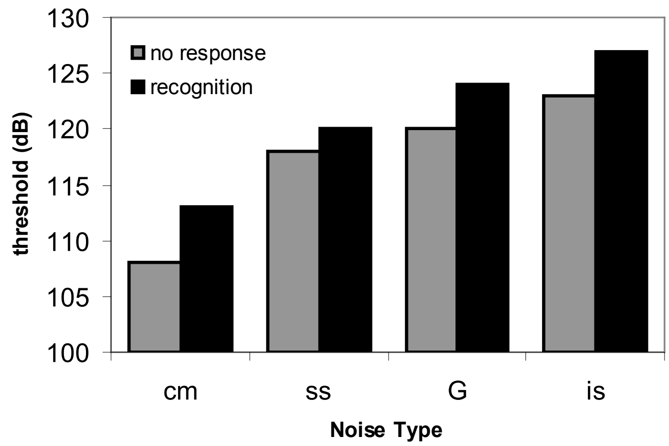

FIG 10. Comparison between recognition and no response thresholds. On average, recognition thresholds are 3.75 dB greater than no response thresholds.

IMPACT/APPLICATIONS

Two main conclusions can be drawn from these studies:

1. Masked detection thresholds can be better predicted from models with both spectral density level and MSC as predictors.
2. Recognition thresholds are about 4 dB greater than detection thresholds.

Most models of auditory masking in marine mammals rely on a single metric related to noise spectrum levels (e.g., critical ratios, 1/3 octave band levels, spectral density levels). All time domain metrics related to noise are discarded. This approach is convenient. However, the data presented here and from FY10 and FY11 demonstrate that noise with equal spectrum levels can result in thresholds that vary by as much as 22 dB. The MSC of the noise in conjunction with spectrum levels provides a much more accurate description of auditory masking for the bottlenose dolphin.

Recognition thresholds can be predicted by detection thresholds. On average, recognition thresholds are about 4 dB greater than detection thresholds. For a sound to have an impact on an animal’s fitness, the sound will have to be associated with a meaning (e.g., recognition of individual conspecfics, alarm calls, potential threats). The 4 dB difference between recognition and detection thresholds is likely related to additional cognitive process required for signal recognition and the associated behavioral response to the signal.

RELATED PROJECTS

None

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